Final Report

TEAM VACAS

- DESIGN AND DEVELOPMENT OF COOPERATIVE UGV SYSTEM -

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SUMMARY

Team VaCAS developed a cooperative unmanned ground vehicle (UGV) system for MAGIC 2010 competition. The system includes a cooperative estimation and control strategy, its software, UGVs and the so-called platform- and hardware-in-the-loop simulator (PHILS) which allows the performance evaluation of multi-UGV system in a virtual environment. Team VaCAS also constructed outdoor and indoor test areas for June site demonstration. Out of the developments, a cooperative estimation and control strategy, which is based on the central decision making and the decentralized Bayesian estimation and control, enables the UGVs to complete the mission of MAGIC robustly while handling uncertainties inherent and significant in real systems in natural environment. For June site demonstration, three UGVs, each having a different set of drive train and sensors, were developed. The PHILS is a multi-computer multi-monitor system and thus allows the performance evaluation of various subsystems. The developed multi-UGV system was first utilized for June site demonstration using PHILS and its ability and proficiency were demonstrated. The system was then applied to the MAGIC mission in a MAGIC Final like test area consisting of three phases, and its ability to complete the entire MAGIC mission was demonstrated. Further, the compatibility of virtual tests to real tests were demonstrated, and the three real UGVs were cooperated with five simulated UGVs in the same environment.

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ORIGINAL PLAN

INTRODUCTION

Statement of the Problem

The Multi Autonomous Ground-robotic International Challenge 2010 (MAGIC 2010) aims to improve the effectiveness, safety, and situational awareness of dismounted ground forces when conducting urban zone reconnaissance and clearance operations and to improve the interaction between humans and teams of cooperative unmanned vehicle systems (UVS). The system will consist of unmanned ground vehicles (UGVs) of two distinct types which will cooperate with each other or act independently. The UGVs will also interact with a simulated unmanned aerial vehicle (UAV) and minimally with a team of operators. As a result of the complex makeup of the system, cooperative control, autonomous task assignment, and the fusion of data from multiple sources will be emphasized. During the challenge, the teams must deploy a group of robust and lightweight UGVs to search a mock urban environment for an unknown number of static and mobile objects of interest (OOI). The UGVs will be required to detect, localize, recognize, classify, and neutralize OOI while providing the operators with a succinct yet thorough overview of the area of operation (AO). Finally, the UGVs must incorporate the uncertainty of all the states in the system and quantify the belief of target states in order to determine that the AO has been cleared of OOI.

Conceptual Solutions Proposed

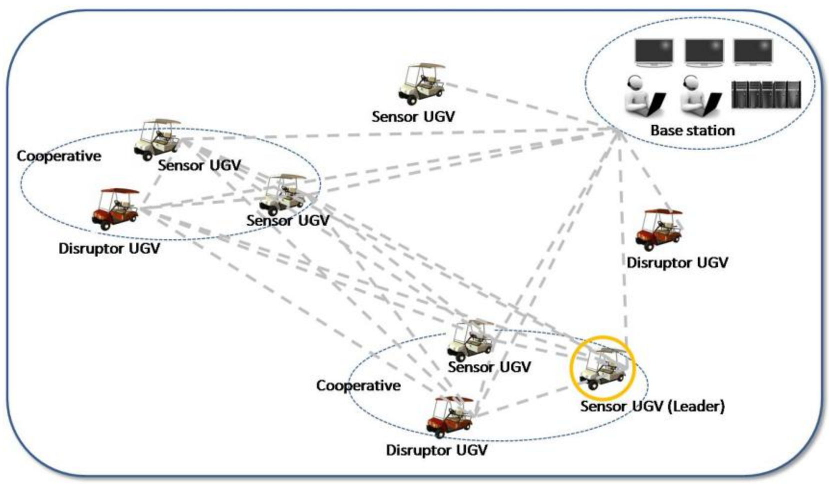


Figure 1 Conceptual solutions proposed

Figure 1 shows the conceptual solutions proposed. The proposed cooperative UGV system will consist of a base station (BS) with two operators and a total of eight UGVs including three disruptor UGVs and five sensor UGVs. Due to the minimum disruptor-to-sensor ratio within the cooperatives [Guidelines 10.4], two cooperatives of one-disruptor-two-sensor UGVs will be in coordination at a time while one disruptor UGV and one sensor UGV will remain independent as extras. These extra UGVs will join coordination when a UGV of the same type has been killed. As a result, two cooperatives can continue the mission with a full complement of UGVs even if one disruptor UGV and one sensor UGV have been disables. Of four sensor UGVs, one sensor UGV is always a leader of the cooperative UGVs. As decentralized estimation and control becomes inconsistent and non-optimal after a certain interval, the leader synchronizes the belief and regenerates the optimal waypoints.

Figure 2 summarizes the features of the proposed cooperative UGV system. All the UGVs are built on the same platform which is commercially available. The platform is of differential steering type for its high manipulability in indoor environments while maintaining a relatively high velocity profile. Sensors mounted on the UGV include those for global positioning, those for localization and mapping and those for dead-reckoning such that all the UGVs and objects of interest (OOIs) can be localized in both indoor and outdoor environments whilst a map is created. Due to the need for image processing and nodal recursive Bayesian estimation, graphics processing unit (GPU) is implemented in addition to a microcontroller unit (MCU) and a central processing unit (CPU).

The UGV system
- 2 operators
- 1 base station
- 3 disruptor UGVs
- 5 sensor UGVs (1 Leader)

UGV
- Commercial platform
- Differential steering
- Sensors
    - Global
    - Local
    - Dead-reckoning
- MCU + CPU + GPU

Estimation
- Multi-level recursive Bayesian estimation
- Synchronously estimated at Leader
- Asynchronously estimated at each UGV

Control and planning
- Strategic planning: rule driven and determined by Leader
- High-/Low-level control: belief/waypoint driven and determined at each UGV.

Data communication
- TCP/IP between BS and UGV
- Multicast IP between UGVs

Figure 2 Summary of solutions

Estimations of UGVs and OOIs are carried out using different RBE techniques by accounting for accuracy and computational efficiency. Each UGV estimates the other UGVs and OOIs in a decentralized manner at high frequency, whereas the leader synchronizes the estimation at low frequency. Control and planning are also performed at different frequencies. Driven at the lowest frequency is strategic planning where the leader creates discrete decision plans for cooperation and distributes them to the other coordinating UGVs. High-level and low-level controls are carried out at every UGV based on various beliefs and attempts to create and follow waypoints respectively with higher-frequency feedback. Data communication is also uniquely equipped in the proposed system. While TCP/IP is utilized between BS and UGV, UGVs communicate with each other via multicast IP.

Graphic Overview of Overall Systems Architecture

The structure of the rules for the MAGIC 2010 makes clear that the overall control of the cooperative UGV system requires a level of sophistication that is not evident in existing commercial, military or academic robotic systems. The requirements of the competition in fact go beyond the approaches that can be found in theoretical or numerical simulation in cutting edge journals in robotics or autonomous systems. For example, some theory has been developed for cooperative search via collectives of autonomous vehicles, but these typically consider the control of single vehicles that act cooperatively with other single vehicles. References [1] and [2] are examples of this type. The MAGIC 2010 requires controlling sub-teams (co-ops) within the overall team. Some theory likewise exists for the networked allocation of vehicles to targets, for example, [3], but again, the necessity that co-ops be used in the MAGIC 2010 goes beyond the working assumptions in these approaches. More importantly, the cooperative search task must be carried out in consideration of engagement with active and mobile enemy teams, which renders existing approaches inapplicable.

Figure 3 shows the graphic overview of the overall systems architecture proposed in the project. Original contributions of this architecture are three multi-level formulations; control, estimation and belief representation. Owing to the multi-level control and estimation formulations, the architecture introduces three feedback loops, aimed at low-level control,

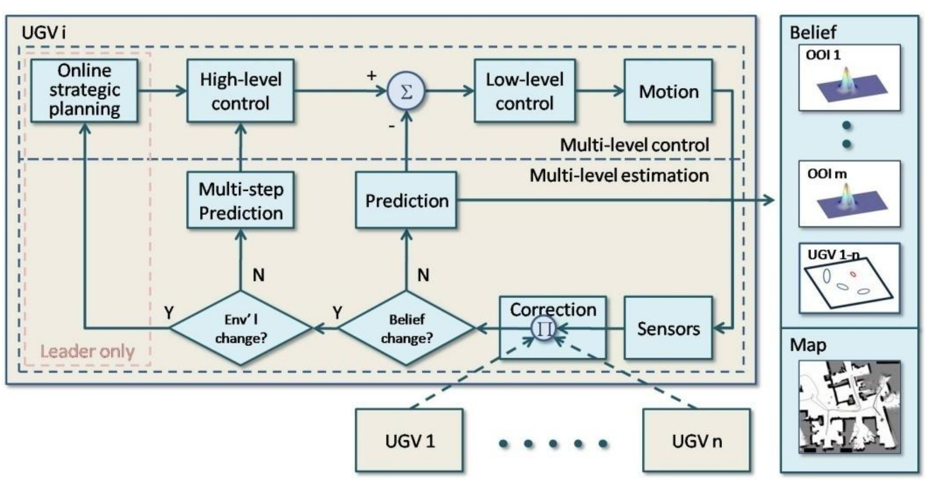


Figure 3 Overall systems architecture

high-level control and online strategic planning. Out of the loops, driven at the highest frequency is low-level control, which is achieved by recursively updating beliefs and resultantly following the specified waypoints. The beliefs updated at each UGV include those on all the UGVs including itself and those on all the known OOIs. If the beliefs have seen a significant change in themselves, the specified waypoints are no longer effective. High-level control creates a new set of waypoints by predicting the beliefs in multiple steps as model-predictive control [4,5] does and extracting and optimizing a quantity such as information entropy and information gain from the beliefs. The least frequent loop allows a new strategic plan to be created. This is essential when OOIs or other environmental factors could force UGVs to re-plan their trajectories based on the rule-based reasoning. Lastly, the multi-level belief representation describes belief of states within the system through three methods. Belief for OOI is constructed in terms of an elemental non-Gaussian distribution while belief of each UGV is in terms of a Gaussian distribution (a mean and a covariance) via the extended element-based method (EEM), an efficient non-Gaussian recursive Bayesian estimator developed by the investigators [6,7], and the extended Kalman Filter (EKF) [8] respectively. Additionally a map is created via occupancy element map (OEM) [7], which was also developed by the authors. It is to be noted here that the use of the EEM is due to the fact that the beliefs of non-cooperating OOIs become heavily non-Gaussian through search whilst the use of the EKF for UGVs is because the states of UGVs are well estimated by Gaussian distributions through communication.

An essential ingredient in this architecture is a multi-level structure that makes provision for the co-ops in the competition. In addition to providing an explicit representation of the co-ops within the overall team, the multi-level structure likewise serves an important role in terms of complexity. It is well known that the determination of policies that map beliefs to actions can be prohibitively expensive in all but the most rudimentary models due to either the dimension of the state space or the exponential growth of histories in time. Casting the formulation in terms of a multi-level structure will reduce computational cost, particularly in the determination of overall strategies for the teams. Team VaCAS has a long history in fielding some of the best robotic systems in the most competitive forums in the world, and moreover, has a unique theoretical expertise with the tools and techniques necessary to field a winning team. The approach taken in this proposal builds on this expertise and synthesizes techniques from game theory, partially observable Markov decision processes (POMDP) and hierarchical state space models to derive a theoretical framework to treat the strategic formulation of the MAGIC 2010 competition.

Work Breakdown and Milestones

Identifying the conceptual solutions and overall systems architecture, Team VaCAS has been broken down into six groups with milestones as follows:

1. **Strategic planning group**: Develops and implements a rule-based decision maker to cope with the rules specified by the organizers with effective strategies.
2. **High-level control group**: Develops and implements a high-level control strategy which ultimately creates waypoints in a finite horizon at a low frequency.
3. **Low-level control group**: Develops and implements a low-level control strategy which ultimately allows the UGVs to follow the specified waypoints while avoiding collision at a high frequency.
4. **System integration group**: Designs or selects all the mechatronic components and integrates all to complete the proposed multi-UGV system.
5. **UGV group**: Designs and develops the UGV platform and implements all the mechatronic components onto the platform.
6. **Perception group**: Develops an image processing and analysis tool specifically for possible OOIs introduced in the MAGIC 2010 but also for standard landmarks and structures.

GROUND VEHICLE COMPONENT & SYSTEMS

Figure 4 shows the ground vehicle components. The major components of each UGV are (1) sensors, (2) actuators, (3) E-stop, (4) processors, (5) wireless modules and (6) battery. Sensors include (a) GPS and compass for absolute localization, (b) laser range finder and two cameras for relative localization and mapping and (c) inertia measurement unit (IMU) in conjunction with encoders for dead-reckoning. Two cameras, mounted on the right and left edges of the vehicle front, are pan/tilt cameras, so that they can be utilized not only a stereo vision range/bearing sensor but also as two independent bearing sensors. Two wireless modules are implemented to relay data between a UGV and the base station or between two vehicles.

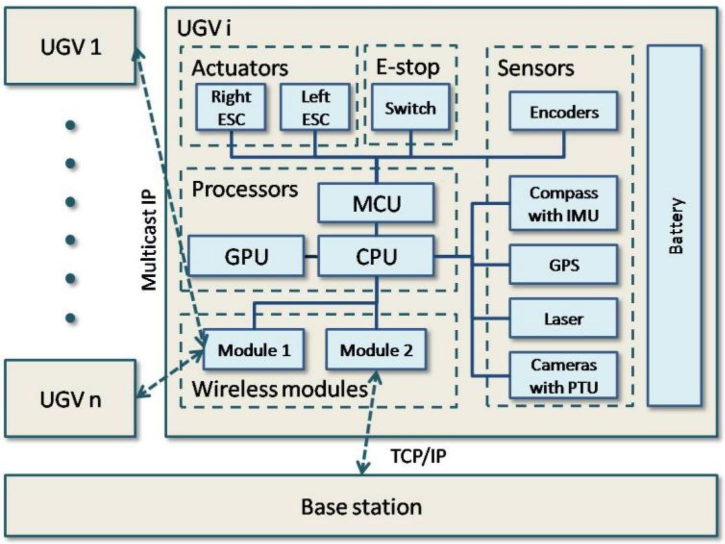


Figure 4 Ground vehicle components

Most unique in the developed system are a GPU and different protocols. Image processing and non-Gaussian RBE, required for estimating the beliefs of OOIs, both see node-by-node calculations. The nVidia GPU, together with CUDA library for general-purpose computing on graphics processing units (GPGPU) accelerates, not only image processing, but also RBE such that real-time RBE is possible. This is indicated by successful demonstrations by the investigators [9,10] using GPU which produced computational speed improvements of more than two orders. The use of two different protocols, TCP/IP and multicast IP, is based on additional research by the investigators [11]. Observing that cooperative autonomous vehicles require frequent communication even at the expense of reliability whilst the communication between the base station and an autonomous vehicle could be less frequent but should be reliable, multicast IP and TCP/IP are utilized for UGV-UGV and BS-UGV communications, respectively.

The chassis of each UGV is based on a Superdroidrobots Heavy Duty 4WD RC All Terrain Robot Kit, shown in Figure 5. Since the UGVs are of a 4WD differential steering design, they are able to not only travel across a wide range of terrains, including gravel paths, but also navigate in confined areas with ease due to their zero tuning radii. The maximum speed is 6.4 km/h and the maximum payload for onboard equipments is 10 kg, while the ground clearance and battery life will be more than 0.1 m and 3.5 hours respectively after slight modifications. The total weight of each UGV with all equipments is less than 20 kg, while the width and height are less than 0.7 m and 1 m, respectively. The mechanical properties of the UGVs well suit the challenges in the MAGIC 2010.

Figure 5 Mechanical base of a UGV

In order to demonstrate the ability of the investigators in developing such UGVs, Figure 6 shows some of the autonomous UGVs developed or integrated by the investigators. Shown in the upper left are the award-winning UGVs (Best UGV Performance Award at MAV08), which have the full capability for cooperation within UGVs and with rotary-wing micro aerial vehicles via BS. The upper right figure shows the vehicle developed for DARPA Urban Challenge, with which Virginia Tech team received the third prize. The pictures in the middle left show a small scale UGV newly developed with full autonomous capabilities; whilst the bottom pictures show full scale autonomous UGVs that the investigators integrated for cooperative control demonstration. Finally, shown in the right end is the article of the ground vehicle that the investigators developed, which was on Washington Post on August 1, 2009,

Figure 6 UGVs developed/integrated by the investigators

UVS AUTONOMY & COORDINATION STRATEGY (BY TASK)

Multi-level Estimation

Multi-level estimation overviewed in Introduction is developed based on the previous pioneering theoretical work of the investigators in (1) Extended RBE (ERBE) [12,13], (2) Partially Observable Markov Decision Process (POMDP) with negative likelihood [14-21], (3) Element-based method with GPU [9] and (4) Multi-level EEM/EKF RBE [13]. In order to explain the significance and originality of the ERBE, let me describe the framework of the standard RBE, which consists of correction and prediction as

$$\begin{cases} b_i^{k+} = f_C\left(b_i^k, l_i^k, m_i^k\right) \\ b_i^{k+1} = f_P\left(b_i^{k+}, p_i^{k:k+1}\right) \end{cases} \tag{1}$$

where b_i^k, l_i^k and m_i^k are the belief, the empirical knowledge and the received messages of UGV i at time k respectively, $p_i^{k:k+1}$ is the Markovian motion model, and b_i^{k+} and b_i^{k+1} are the corrected belief at time k and the predicted belief at time $k+1$. This framework suffices if the belief is of a static OOI or if the RBE technique is the one which does not maintain the belief space configuration such as EKF and particle filters. However, if the OOI is mobile and is not detectable (Some OOIs in MAGIC 2010 are indeed mobile and not detectable), its belief must be maintained with its space configuration dynamically. The ERBE extends the standard RBE by additionally introducing the reduction and expansion of the belief space as

$$\begin{cases} B_i^{k+} = f_R\left(B_i^k, l_i^k, m_i^k\right) \\ B_i^{k+1} = f_E\left(B_i^{k+}, p_i^{k:k+1}\right) \end{cases} \tag{2}$$

where B_i^k, B_i^{k+} and B_i^{k+1} are the original, reduced and expanded belief space.

In order to maintain and update the belief effectively within the framework, the POMDP developed by the investigators defines the probability of detection and constructs a negative observation likelihood if the OOI is not within the field-of-view and thus not detected. Let the unknown state be given by x_i^k. The observation likelihood is given by

$$L_i\left(x_i^k \mid l_i^k\right)=\begin{cases} p\left(x_i^k \mid l_i^k\right) & \text{Detected} \\ 1-P_d\left(x_i^k \mid l_i^k\right) & \text{Not detected} \end{cases} \tag{3}$$

where P_d is the probability of detection and p is a likelihood defined when the OOI has been detected. Despite its effective estimation, it is however to be remarked here that the developed POMDP will make the updated belief severely non-Gaussian. The RBE technique, therefore, must have the ability to update a severely non-Gaussian belief with its space configuration dynamically.

The element-based method developed by the authors adopts the concept of the grid-based method, which could satisfy the requirements by representing the belief space in terms of a set of grid cells, but reformulates the grid cells by elements with shape functions such that the belief space is represented by fewer parameters and thus is computed less expensively. The past experimental investigations of the authors show the 450% computational improvement by the element-based method over the grid-based method and further the 97% parallel efficiency by its implementation into GPU (Speedup of 31.3 for 32 processors; Figure 7). As a result, RBE on a belief space equivalent to 1,000,000 grid cells was performed within 0.01 second per iteration, demonstrating its real-time capability for RBE over a large belief space.

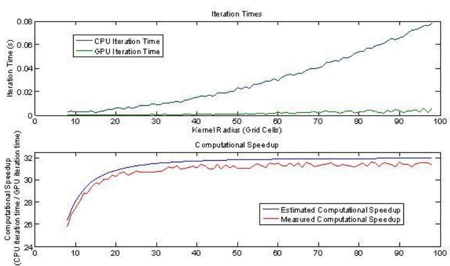


Figure 7 Computation time and speedup

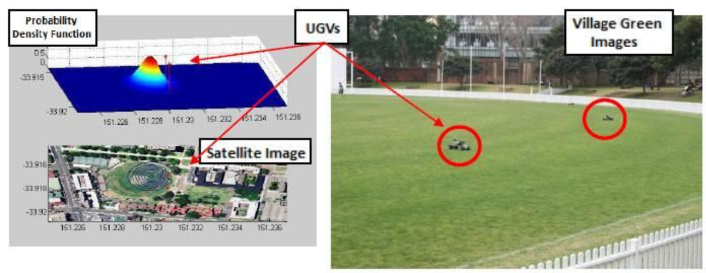


Figure 8 Multi-UGV cooperative control experiment

Lastly, ERBE using EEM (the element-based method extended to dynamically update the belief space) and EKF is another technique developed by the investigators to reduce the computational load. Since UGVs can receive the observed states of the other UGVs through communication, the states of UGVs can be well estimated by EKF, which requires only the update of the mean and the covariance rather than the belief distribution on the entire belief space and thus reduces the computational load.

The series of technical developments will maintain beliefs most reliably and effectively while lightening the computational load and allowing real-time capability for estimation and usability even for low-level control. In addition, asynchronous estimation on each UGV in a decentralized manner with only occasional synchronization by the leader makes the ERBE highly scalable without delay by the increase of the number of UGVs. To date, the practical applicability of the developed multi-level estimation was experimentally investigated as shown in Figure 8 using up to 4 UGVs. The experimental results have well demonstrated the real-time capability even in a real outdoor environment.

Multi-level Control

Low-level Control

Although low-level control is most commonly achieved deterministically, the proposed architecture designs low-level control with the beliefs updated recursively as input. This is due to the following reasons:

- **Generality**: The deterministic control can be treated as a special case of the belief-driven stochastic control. Since high-level control is based on RBE, the formulation of low-level control based on RBE allows both to be described in the same framework.

- **Richness**: In case of communication loss, obstacle detection and other unexpected situations, following the specified waypoints no longer a solution. Having various uncertainties, belief-driven control that can utilize such uncertainties and determine its control from richer information may handle the situation better.

To first show the ability in waypoint tracking, let the targeted waypoint at time $k+1$ and the mean of the estimated position of the UGV i at time k be x_t^{k+1} and $\overline{x}_i^{k+}$ respectively. Having the position of the UGV at time $k+1$ predicted as $\overline{x}_i^{k+1} = f_{Pm}\left(\overline{x}_i^{k+}, u_i^k\right)$, the low-level control finds the control action $\tilde{u}_i^k$ as

$$\tilde{u}_i^k = \arg\max \left\| x_t^{k+1} - f_{Pm}\left(\overline{x}_i^{k+}, u_i^k\right) \right\|^2 \tag{4}$$

Note that the low-level control is belief-driven because the mean is a property of belief represented by a Gaussian distribution. Since the low-level control is performed at high frequency, it is adequate to assume that the UGV is well approximated by linear equations. As a consequence, Equation (4) will be reformulated as a Linear-Quadratic-Gaussian (LQG) problem and solved analytically for fast computation.

When pre-specified waypoint control is no longer a solution due to communication loss, obstacle direction or other unexpected situations, control should be based on the beliefs of others such as the detected obstacle, UGVs or OOIs at least until high-level controller can find a new set of waypoints. Since the beliefs could be Gaussian or non-Gaussian, the control solution $\tilde{u}_i^k$ could be generically expressed with beliefs and belief spaces as

$$\tilde{u}_i^k = \arg\max J\left(u_i^k \mid b_i^{k+}, B_i^{k+}, p_i^{k:k+1}\right) \tag{5}$$

This problem requires optimization, which consumes more computation than the derivation of analytical solution due to the repetition of predictions. However, due to the determination of decentralized control actions for only one-step look-ahead, only two parameters (two motor speeds) need to be optimized and the computation time does not increase significantly. The past experiments by the investigators show that the belief-driven low-level control can be achieved within 0.1 second on a belief space equivalent to 1,000,000 grid cells, indicating its ability for real-time control [9,10].

High-level Control

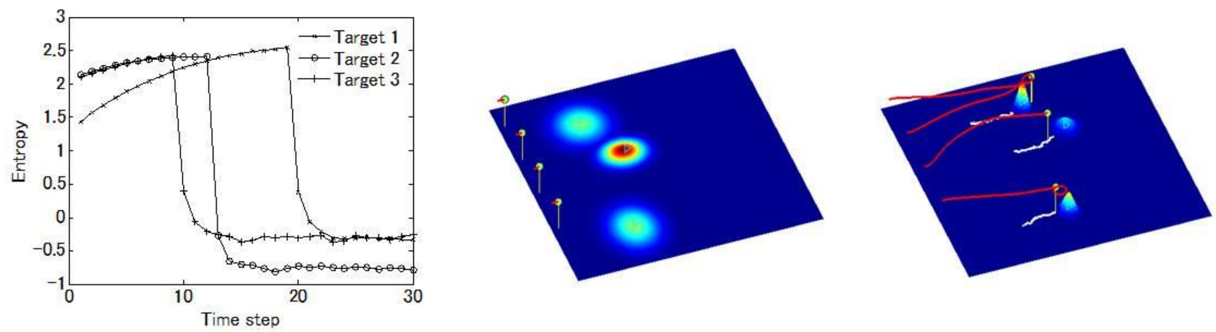
The proposed system implements high-level control to engage UGVs with OOIs assigned through strategic planning. Due to the development of the ERBE framework, the high-level control, aimed at determining control actions on a finite time horizon up to time $k+n_k-1$, is given by an extension of the low-level control:

$$\tilde{u}_i^{k:k+n_k-1} = \arg\max J\left(u_i^{k:k+n_k-1} \mid b_i^{k+}, B_i^{k+}, p_i^{k:k+1}\right), \tag{5}$$

which is solved by performing prediction $n_k n_l$ times where n_l is the number of optimization loops. Since the number of control parameters is $2n_k$ and thus makes n_l large, the computation time becomes significant. In order to achieve high-level control within the order of a few seconds, the technique implemented keeps n_k low by differing the control time interval from the simulation time interval and specifying the control time interval by a multiplication of the simulation time interval. This reduces n_k by the multiplication factor although the optimality of the solution is weakened. Similarly to the low-level control, the feasibility of this approach has already been demonstrated experimentally [22].

Since the primary aim of the high-level control is to engage UGVs with OOIs, the tasks to be defined are search (when OOIs are not detected) and tracking (when OOIs are detected). The investigators are the pioneers of the search-and-tracking, writing the first paper on this topic [18]. In their approach, search-and-tracking is not manipulated by control actions. It is determined by the belief update in measurement as Equation (3) described. Since the negative likelihood swipes the observed region of the belief space, search can be performed similarly to tracking by simply moving towards a high belief region without re-visiting the observed regions. If the belief of the OOI of concern is given by $p\left(x_o^{k:k+n_k} \mid u_i^{k:k+n_k-1}\right)$, the control solution can be uniformly computed by minimizing the information entropy (or maximizing the information gain):

$$\tilde{u}_i^{k:k+n_k-1} = \arg\min -\int p\left(x_o^{k:k+n_k} \mid u_i^{k:k+n_k-1}\right) \log p\left(x_o^{k:k+n_k} \mid u_i^{k:k+n_k-1}\right) dx_o^{k:k+n_k} \; . \tag{6}$$



(a) Information entropy (b) k=1 (c) k=20

Figure 9 Cooperative search and tracking

Figure 9 shows the result of cooperative search and tracking that the investigators reported previously where four UGVs search for and track three targets. It is shown that the proposed technique could successfully search for and track targets by minimizing the information entropy. The graph also shows that the proposed technique could discover targets tracked but lost early since the belief is maintained unlike conventional deterministic techniques.

Strategic Planning

Strategic planning against rules regulated for MAGIC 2010 involves the study of knowledge representation and reasoning. While learning can automate the process and offer more academic contents, the strategy adopted is the manual construction of an expert system that constructs database and knowledgebase and associates them via a number of if-then rules. The main reason for the selection of this approach is the requirement of constructing only a limited number of rules for the MAGIC 2010. Due to the lack of time that was available after the Participants Conference in August 2009, database, knowledgebase and rules to apply for MAGIC 2010 scenario and rules have not been developed, yet. Members of the strategic planning group have been however identified. There is enough staff and time available to construct and implement all before the MAGIC 2010.

Table 1 Sensors and processors

Sensors/Processors	*Model*
2 cameras with PTU	Toshiba IK-WB15A
Laser range finder	Hokuyo UTM-30LX
GPS	Garmin GPS 18x 5Hz
Compass with IMU	Ocean Server OS500-S
Encoders	Platform built-in
Microcontroller	AVR Atmega 88PA
CPU/GPU	nVidia ION (Intel Atom CPU/nVidia GeForce9400)

Sensors, Processing & Mapping for UGVs

Table 1 shows the sensors and processors selected for the UGVs. They may be replaced by other systems if systems with better performance in cost or technical specifications are found. Most importantly, global positioning, localization/mapping and dead-reckoning can be achieved by the sensors; GPS and compass for global positioning, 2 cameras and laser range finder for localization/mapping and IMU and encoders for dead-reckoning. The microcontroller and the CPU/GPU set were selected with the extensive experiences of the investigators in using these systems for real-time ERBE and image processing.

So as to develop a map within the ERBE framework, the technique proposed in this project is the occupancy element mapping, which is also the original contribution of the investigators. This technique, similarly to the occupancy grid mapping [23], represents the probability that each cell is occupied, but the probability is variably represented using shape functions similarly to the element-based method, requiring less computational efforts to achieve the same accuracy. Because of the usage of the same data structure and method, the occupancy element method can also take significant advantages from its implementation onto GPU. During the map creation,

OPERATIONS IN GPS-DENIED ENVIRONMENTS

GPS data from satellites may become completely unavailable if UGVs are in indoor environments. While the global sensors including a GPS and a compass and the relative sensors including cameras and a laser range finder are used for global positioning and mapping in outdoor environments, the UGVs additionally use encoders and an IMU to compensate for the unavailability of GPS. Much work has already been reported for indoor localization and mapping in the name of indoor Simultaneous Localization and Mapping (SLAM) [24]. Similar to such work, the technique to be used in the project will also (1) use the last reliably available data as the reference global position, (2) estimate the position after movement using encoders and IMU, and (3) correct the position by pattern-matching the observable static objects using cameras and a laser range finder.

PROCESSING AND FUSION OF PROVIDED METADATA (FROM UAV)

The vector map of the challenge area and locations of OOI detected by the UAV are extracted from the provided metadata. To extract the vector map, image processing and analysis techniques are used to classify and locate objects in the provided overhead EO image. The locations of the classified objects are stored in the vector map that is examined by the operators. Due to the limited resolution of the EO image and detected OOI locations in the metadata, the uncertainties of object and OOI locations are high and thus also included in the vector map. The vector map gives a global sensor reading that is fused with more accurate local sensor information collected by UGVs' explorations in real time to yield better belief of OOI locations and map.

HUMAN-MACHINE INTERFACE (HIM)

In all the stages, most decisions are made autonomously, but the operators are responsible for assessing the decisions through the HMI and overriding them if necessary. For example, if any UGVs are lost due to sniper's action or undetected OOI, the base station proposes re-tasking and re-forming the teams based on the belief of OOI and status of UGVs. The operators then examine the proposed solutions and decide to accept or to modify the solutions.

Due to the interaction of two operators with eight UGVs, it is essential that the human-machine interface (HIM) effectively allow the operators to interact with the UGVs and monitor their performance.

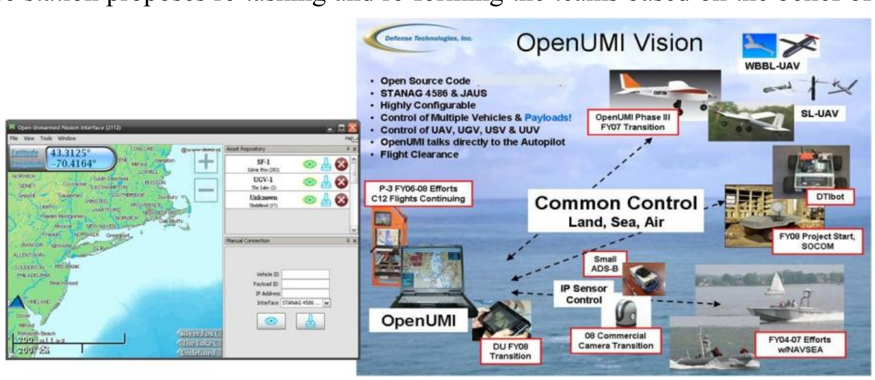


Figure 10 OpenUMI

The Virginia Tech team will use a high-performance HMI which will be extensively developed by their industrial partner, Defense Technologies, Inc., who is the developer of the Open Unmanned Mission Interface (OpenUMI). Figure 10 shows a graphical user interface of the OpenUMI as well as the graphical summary of its features. The OpenUMI provides an interoperability on a common control operator interface for multiple, heterogeneous unmanned vehicle using the STANAG 4586 and JAUS standards. Open UMI also provides cross platform support and is tested in the Windows and Linux environment, so that it will be immediately usable for UGVs of the Virginia Tech team. Traditional control stations suffer from limitations of only being able to control a single vehicle or a single type of vehicle. The OpenUMI has been developed to control any unmanned system concurrently, including UGVs, UAVs and SUVs.

OPERATIONAL APPROACH/MISSIONS OPERATIONS STRATEGY

The overarching mission operations strategy is to finish the mission as soon as possible while minimizing damage to UGVs and non-combatants. Accordingly the behavior of the UGVs will progress from lowest risk to highest risk so that increased situational awareness that develops throughout each phase will mitigate the risk of behaviors such as searching in buildings or confined spaces. The strategy therefore is divided into three stages within each phase. In stage 1, two sensor UGVs with video cameras equipped with telephoto lenses search for and identify hostile OOI and non-combatants and neutralize hostile OOI from long distances. Long-distance searching is extremely effective in large areas and protects the UGVs from mobile hostile OOI's attack. These UGVs are protected from static OOI by the other two sensor and two disruptor UGVs sweeping paths. The goal in this phase is to quickly clear the lowest risk regions thus creating a safe avenue of swift retreat in the event that UGVs need to flee a mobile OOI in subsequent stages. In stage 2, after successfully locating and neutralizing most hostile OOI in open and easy to clear regions, two teams, each with one disruptor and two sensor UGVs with wide-angle zoom video cameras, are sent to search for remaining OOI and a build high-resolution map in outdoor unexplored areas. Here the teams assume slightly more risk, searching confined spaces, areas obscured from aerial images such as beneath trees, and blind spots around building corners. Stage 2 ends when the team and operators are confident that the exterior areas have been cleared of OOI. Finally in stage 3, the two teams continue their exploration and neutralization in open buildings. In all stages confidence that an area had been cleared will be created by both a low probability of an undetected OOI and low information entropy associated with the location of objects within the area. The scalar values of probability of detection and information entropy that will serve as thresholds to systematically transition between stages. These thresholds will be tuned through testing the final vehicles in real buildings at Virginia Tech.

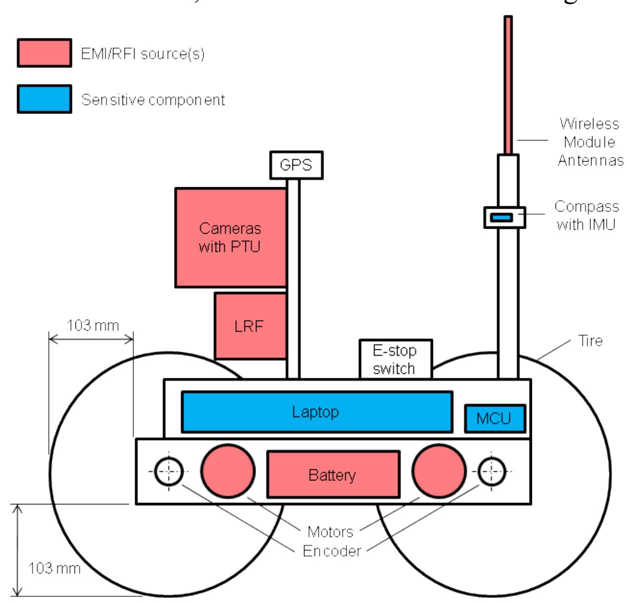


Figure 11 Simplified layout of developing UGV

RISK REDUCTION STRATEGY

EMI/RFI & Electrical

Reduction of electro-magnetic interference (EMI) and radio frequency interference (RFI) is achieved through two solutions, which are shielding and proper placement of all EMI/RFI sources and sensitive components. Figure 11 illustrates a cross-sectional side view of a simplified layout of the developing UGV, with color highlighted EMI/RFI sources and sensitive components. All the sensitive components are shielded by electrically grounded aluminum cases. On the other hand, the compass with IMU, which is extremely sensitive to EMI/RFI, is located at a position not in the radiation pattern of the wireless module antennas and far away from the other major EMI/RFI sources. To make internal communications more robust to EMI/RFI, all signal transmissions between electrical devices are in digital forms.

For fire prevention, a few safety measures are taken to reduce the risks of short circuit and overdrawing current from the battery. In order to prevent short circuit in raining conditions, all the electrical components are located in water-proof cases. If a short circuit occurs in some devices, fuses will cut the power to the devices to avoid overheating. On the other hand, the battery voltage is measured by the MCU and monitored by the operators through the HMI in the BS. The operators are responsible for appropriate high-level path planning to prevent running out of the battery before entering designated servicing zone (DSZ), while the MCU will trigger a termination mechanism to avoid flattening the battery when the battery voltage is too low.

Vibration & Physical

Vibration isolation in each UGV is achieved by the uses of large and deformable wheels and vibration absorption materials that support critical components sensitive to vibration, such as the laptop. The front wheels and rear wheels, as the front-most and rear-most parts as illustrated in Figure 11, also act as soft bumpers to sustain impacts caused by collusion. To reduce the damage to surrounding caused by collision, sharp edges and corneas are avoided or covered by soft materials. To diminish the risk of rollover, most heavy components, including battery, motors and laptop, are placed as low as possible to minimize the height of the center of mass. In addition, the maximum speed and tuning rate are limited by onboard software.

Modeling & Simulation

Figure 12 shows the modeling and simulation systems that have been developed by the investigators and will be used for MAGIC 2010. In addition to the traditional hardware-in-the-loop simulation, the cooperative control will require the simulation of real-time performance of sensor platforms under cooperation due to the high complexity of cooperation. This so-called Platform-In-the-Loop Simulator (PILS) has been uniquely developed to satisfy such need while also allowing real platforms to participate in the cooperation. As shown in Figure 12(a), the PILS connects computers through the server-client system. Since this server-client system allows different visualization tools to be communicated, there is no need for developing a new visualizer for cooperative control. Figure 12(b) shows a PILS that is displaying cockpit views from eight cooperative UAVs (eight monitors above), locations of the UAVs on Google Map (bottom-left) and Google Earth (bottom-middle) and the belief of a target (bottom-right). Shown in Figure 12(c) is a mobile PILS, which has been developed to take to the outdoor experimentation.

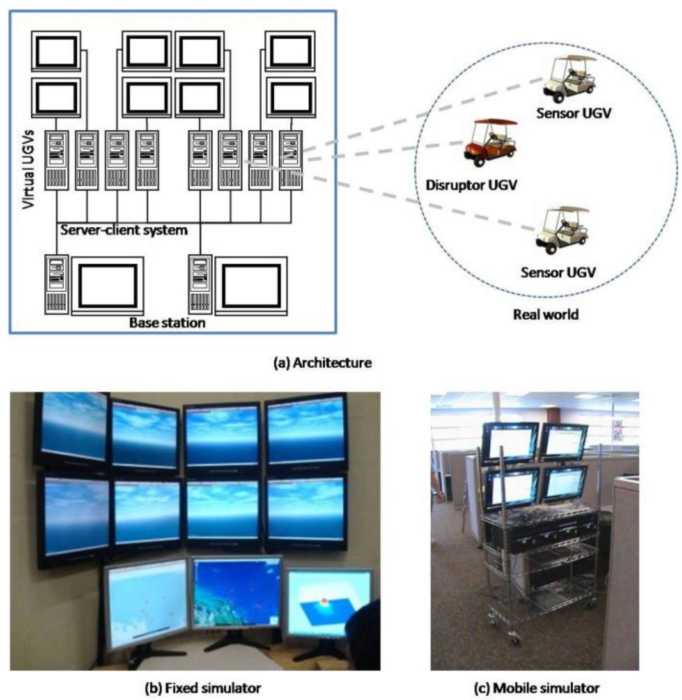


Figure 12 The platform-in-the-loop simulator

Safety, E-Stop, Freeze & Lost-link

To reduce the risk of injury caused by the UGVs, a number of safety features will be incorporated in the UGVs. First, each UGV is equipped a termination mechanism ("E-stop") that deactivates all the ESCs electrically by disconnecting their power and applying brake on all the motors mechanically. When any equipment failure or dangerous behaviors, such as out of boundary, crashing and speeding, are observed by any of the onboard sensors, operators or judges, the MCU, laptop, operators or judges can activate the "E-stop". The activation by operators is achieved through the HMI in the BS and the wireless module 2 connected to the laptop, as shown in Figure 4. On the other hand, the judges can remotely trigger "E-stop" via handheld remote controls and a separate wireless module connected directly to the MCU and E-stop, regardless the status of the laptop.

Second, an administrative stop ("Freeze") is implemented on each UGV. "Freeze" is achieved by the MPU sending commands to stop all ESCs until receiving a command to cancel "Freeze". "Freeze" can be triggered in a manner similar to "E-stop", but it differs from "E-stop" in that it does not apply mechanical brake on and does not cut power to each motor. Third, when each UGV starts, the laptop and MCU check and ensure all the onboard equipments functioning well before activating the ESCs. Last, in the event of lost-link to or unstable communication with the BS, the UGV triggers "Freeze" immediately as the operators cannot monitor the UGV status.

Communications Architecture

To improve the robustness of wireless communications, which are not reliable especially in non-line-of-sight conditions or out of range, three communication protocols are utilized to suit different requirements of reliability for remote "E-stop", BS-UGV and UGV-UGV communications. For remote "E-stop", the judges can remotely trigger "E-stop" through their handheld devices, which send "E-stop" commands continuously to a dangerous UGV. Once the onboard MCU receives an "E-stop" signal that passes a checksum test, "E-stop" will be triggered. Since the judges who observe dangerous behaviors of the UGV are usually very close to the UGV, the wireless communication is very reliable.

Besides, the BS-UGV communication uses the TCP/IP protocol that is very reliable due to its abilities of error detection and retransmission of lost data. The reliability of the BS-UGV communication ensures that the operators in the BS can monitor all UGVs' faithful sensor readings and stop some UGVs if necessary for safety purposes. Because the UGV-UGV communication does not require high reliability, it uses multicast IP, which is less reliable, for high-speed communication.

Spectrum Plan & Usage

The spectrum usages are for BS-UGV and UGV-UGV communications and remote "E-stop". All of them are planned to use 2.4 GHz spectrum, which is open and safe for public. They can share the same 2.4 GHz spectrum by using different channels without interfering each other. To reduce interferences to other 2.4 GHz wireless devices near the MAGIC 2010 field and to extend the range of UGV-BS communication, directional antennas pointing to the field are used in the BS.

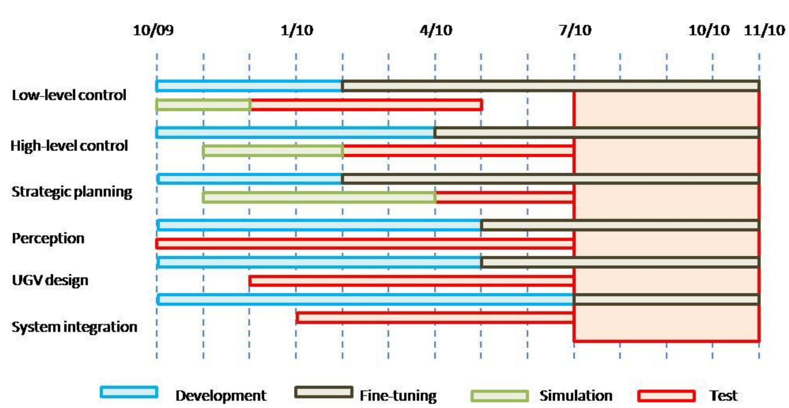


Figure 13 Gantt chart

Test Plan

The Virginia Tech team possesses a number of UGVs in various sizes including those shown in Figure 6. Since experimental tests can be performed using the existing UGVs at any time, tests of perception will start in October, 2009 while UGVs for MAGIC 2010 are being developed. Figure 13 shows a Gantt chart indicating testing period as well as development, fine-tuning and simulation periods. All the developments are to be completed by July, 2010, and the performance tests of integrated UGV system will start subsequently and continue in a similar test site offering a large outdoor space and indoor buildings until the system is sent to Australia.

Figure 14 shows a 5-acre JOint Unmanned Systems Testing, Experimentation and Research (JOUSTER) test site, which is located in the Danville campus of Virginia Tech. The 6.6 million dollar JOUSTER project sponsored by US Department of Defense has created one of the best university test environment for unmanned systems research with various research facilities and unmanned vehicles. The land and the research building will be used as the test environment for the rehearsal of MAGIC 2010.

(a) JOUSTER test site

(b) View from control room

Figure 14 JOUSTER test site

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DEVELOPED SYSTEM

COOPERATIVE CONTROL STRATEGY

Central and Decentralized Control

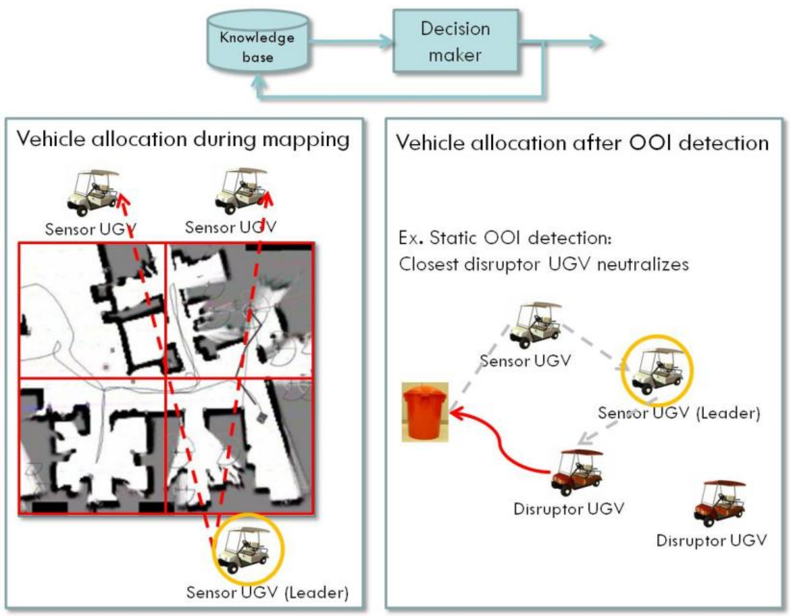

Figure 15 Central decision making by lead UGV

In accordance with the strategy proposed in Figure 1, the proposed strategy has incorporated two types of hierarchical control approaches. Figure 15 shows the highest control approach, which is the discrete decision control to be centrally made by the lead UGV. In order to enable robot control as decentrally as possible, the lead UGV makes a discrete decision whenever necessary. Such circumstances include the vehicle allocation during mapping and vehicle allocation after OOI detection. In the vehicle allocation during mapping, the lead UGV allocates an area to each UGV so that each UGV can be decentrally controlled. This also enables global mapping at maximum efficiency because of the introduction of no overlapping area. Vehicle allocation after OOI detection, meanwhile, allocates a disruptor UGV to the detected OOI. The allocated UGV therefore neutralizes the detected OOI, and the other disruptor UGVs can work independently for their own tasks.

Bayesian STLAM

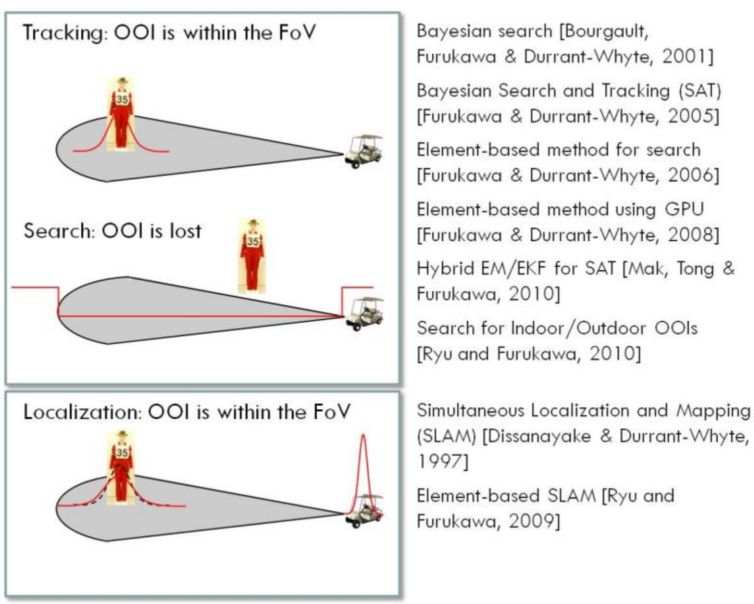

Figure 16 Search, tracking and localization

Figure 16 shows the illustration of the Bayesian search, tracking and localization techniques implemented in the developed system. Due to the near-Gaussian nature of the likelihood of observed OOI, tracking is carried out using Extended Kalman Filter (EKF). Search, on the other hand, is performed by the element-based method because the likelihood is heavily non-Gaussian. Similarly to tracking, localization occurs when an OOI is within the field of view (FoV). Therefore, EKF is used for localization.

Tracking and localization are computationally inexpensive processes since only the mean and covariance need to be updated. They are thus calculated on a central processing unit (CPU). On the other hand, search requires grid-by-grid computation, and a graphics processing unit (GPU) is additionally utilized.

Figure 17 illustrates the specifications of the developed occupancy mapping technique and one of the map results. The developed occupancy element mapping (OEM) technique differs from the conventional occupancy grid mapping (OCM) technique only in cell representation. The difference by the use of finite elements with shape function enables the OEM to be more accurate than the OCM without much increase in computation time.

The OEM is implemented to be carried out on a nodal basis. The OEM has therefore been implemented on a GPU so that the computational efficiency can be dramatically improved.

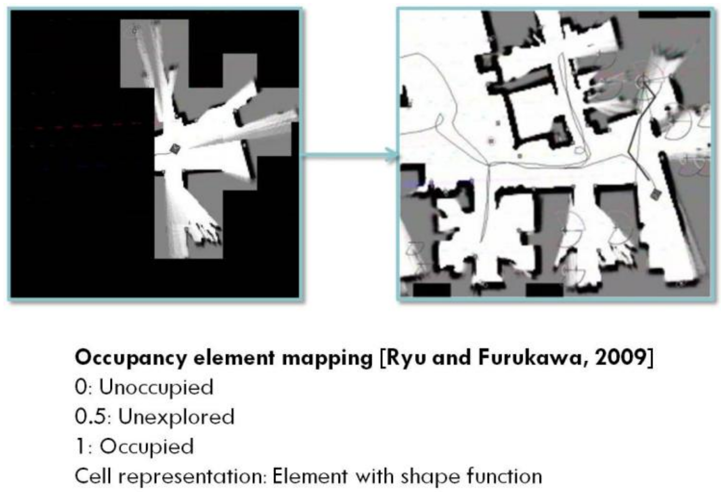

Figure 17 Mapping

PLATFORM- AND HARDWARE-IN-THE-LOOP SIMULATOR AND PERFORMANCE EVALUATION

Figure 18 shows the design of the platform- and hardware-in-the-loop simulator (PHILS), which enables the simulation and performance evaluation of the multi-UGV system. In order for simulation and performance evaluation in a real-time environment, the system consists of multiple computers, multiple monitors and a Gigabit switch. The visualizer that creates a virtual environment is FlightGear, which is an open-source tool originally developed for flight simulation. In the creation of a virtual environment with a system having multiple computers, a FlightGear server is run on a computer having Linux as an operating system. Computers as many as UGVs, on the other hand, each runs a FlightGear client and share the environment produced by the FlightGear server. These computers are also each used to calculate the motion of a UGV. It is often useful to visually monitor the motion and sensing of each UGV. For this reason, a monitor is connected to each computer. Each computer has a GPU, so graphics can be shown at accelerated speed. Since FlightGear allows several views from a vehicle, these views can be shown on each monitor. Additionally, the field of view of a camera mounted on a UGV has been also made possible to monitor. Motion of OOIs need to be also updated in real time, but it is not important to monitor their motion. In order for real-time calculation, the multiple OOIs have been implemented on a GPU. Other elements consisting a

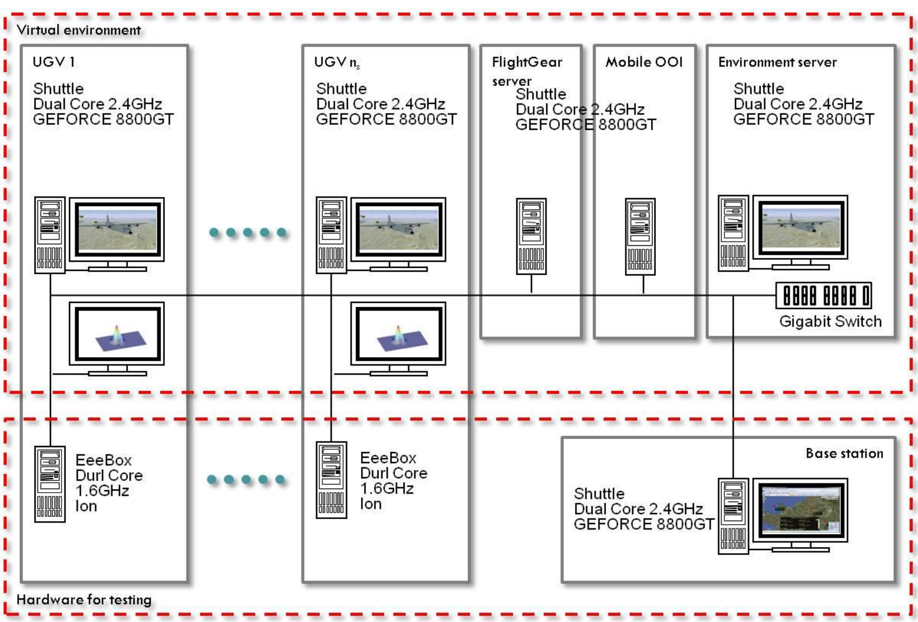

Figure 18 Design of platform- and hardware-in-the-loop simulator

real-time virtual environment in a multi-computer environment, such as terrain maps, time and communication are managed by an environment server. Computers are connected via a Gigabit switch. This is primarily to achieve real-time simulation but also to control wireless communication environments, which generally has the communication speed of the order of 100Mbs or less. In addition to communication delay, it is also possible to introduce communication loss. The communication delay and loss are controlled by the environment server.

Shown at the bottom half are the computers that are to be tested in real environments. These include computers to be mounted on UGVs and a Base Station computer. In order to monitor the performance of capability of autonomy, the PHILS provides a monitor for each UGV.

Figure 19 shows the developed PHILS. A big screen is connected to one of the computers with FlightGear client and shows the motion of all the UGVs. Computers calculating UGV motions are each connected to a 40 inch monitor. Base Station computer and on-board computers are located on the right-hand side. The 19 inch monitors connected to the on-board computers each show a map created and OOI locations identified by a UGV, whereas the monitor of the Base Station shows a combined map.

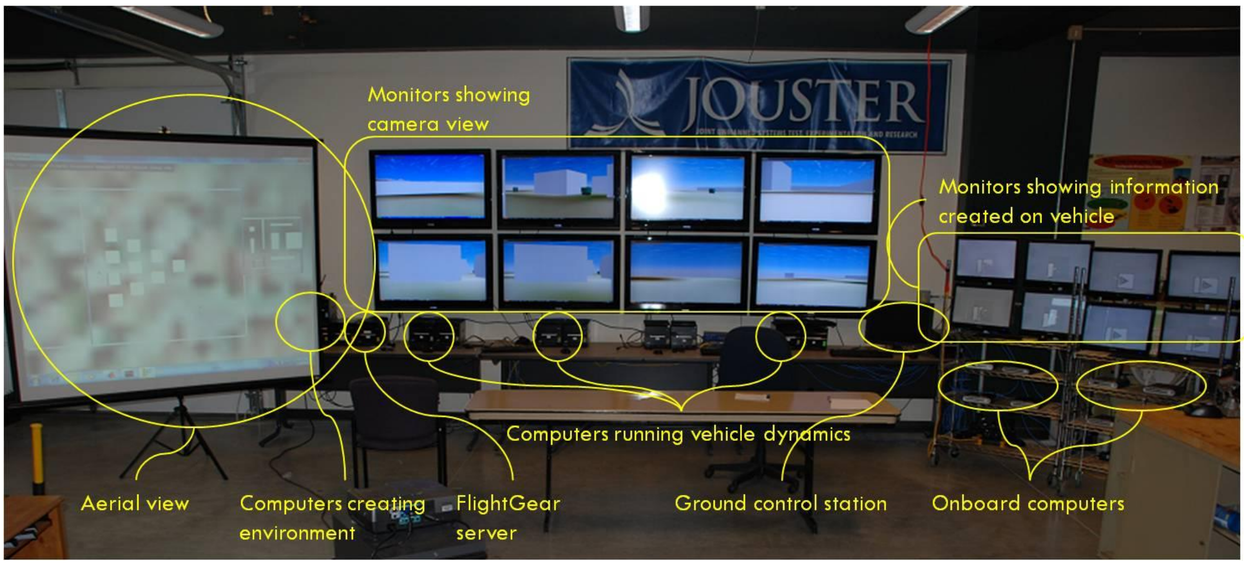

Figure 19 Platform- and hardware-in-the-loop simulator

UNMANNED GROUND VEHICLES

Figure 20 shows three UGVs developed during the project. In order to identify the best-performance UGV, three UGVs have different designs and configurations. UGV 1 utilizes Ackerman steering drive train and thus is good at high-speed drive. Field tests have shown that the maximum speed is over 20 km/h. On the other hand, the Ackerman steering driven train does not have high maneuverability. It has been generally developed to drive in outdoor environments, which generally have less obstacles and thus enable high-speed drive. Sensors mounted on the UGV 1 include GPS for outdoor navigation, LiDAR for obstacle avoidance and mapping and camera for OOI detection and localization. UGVs 2 and 3, meanwhile, have a differential steering platform. The UGVs therefore achieve high maneuverability at the expense of high velocity. UGV 2 has IMU, compass and encoders in addition to the GPS, LiDAR and camera. The compass and IMU makes the UGV localization in indoor environments, and the encoders further enables the indoor localization even when no landmarks can be observed. The UGV however has only three wheels and thus does not drive fast. UGV 3 has all the sensors of UGV 2 except encoders. As a result, it is essential that UGV 3 see some landmarks for successful continuous localization unlike UGV 2. However, UGV 3 can run as fast as 15 km/h unlike UGV 2, the maximum speed of which is around 6 km/h.

Figure 20 Developed UGVs

TEST AREA CONSTRUCTION

Figure 21 shows the test site arranged for Team VaCAS. The test site is part of Computational Multiphysics Systems Laboratory in Institute for Advanced Learning and Research, Danville, VA, which is directed by the principal investigator. The test site utilizes two buildings and one outdoor field. The Ground Control Station (GCS) is located in one building whereas another building provides an indoor environment. The GCS is about 100 m away from the outdoor field and the indoor test area to satisfy the requirements.

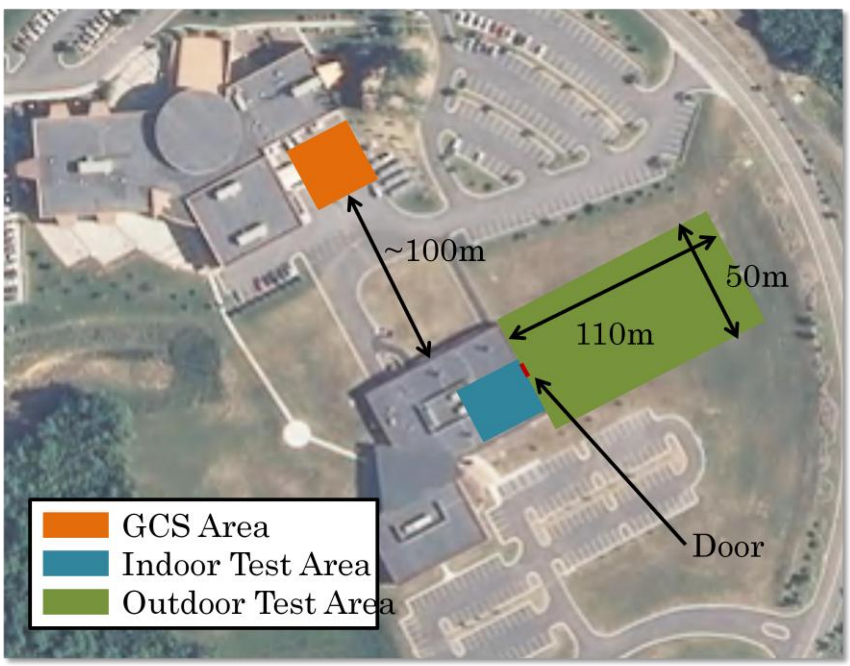

Figure 21 Test site

Figure 22 shows the dimensions of the outdoor indoor test areas. Two empty rooms were utilized to set up indoor obstacles. The obstacles were all made to follow the guidelines of the MAGIC documents and the instructions of the National Institute of Standards and Technology (NIST).

Figure 23 and Figure 24 show the outdoor field and the indoor test area with obstacles constructed according to the guidelines. A total of ten boxes, each with dimensions of 4 m by 4 m by 1.2 m, have been constructed and placed as instructed. Other obstacles include fences.

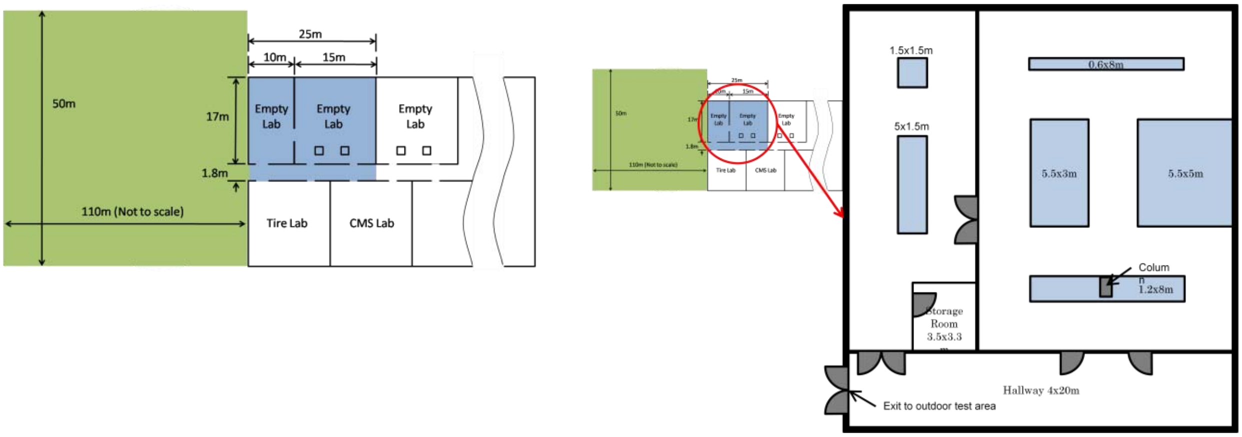

Figure 22 Dimensions of outdoor and indoor test areas

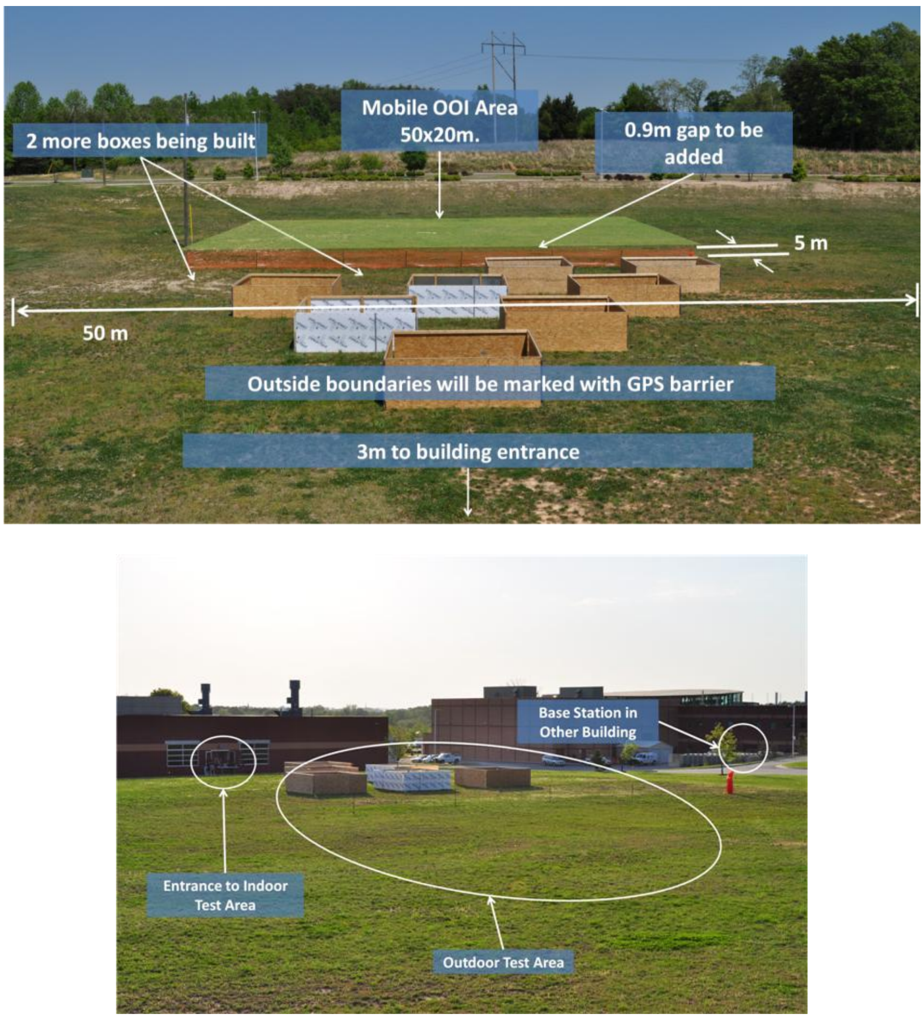

Figure 23 Outdoor test area

Figure 25 shows the capability of monitoring the test areas by cameras. A total of seven cameras have been installed, and the installation has resulted in covering 90% of the outdoor and indoor test areas for monitoring.

Figure 24 Indoor test area

Figure 25 Camera monitoring capability

Simulation and Experimental Results

Figure 26 shows two virtual outdoor and indoor environments that were modeled. The left figure is the test area designed by following the guidelines for June site demonstration. By being informed of the coarse configurations of the Phases I-III regions, the right one shows a test area resembling the demonstration site of the MAGIC Final. The developed PHILS can easily model such areas and allow the simulation and performance evaluation of a multi-UGV system.

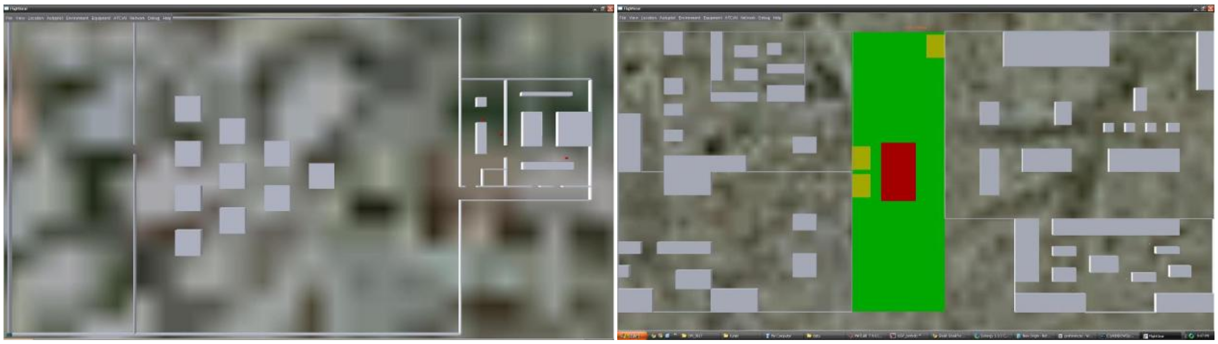

Figure 26 Virtual outdoor and indoor environments

In order to evaluate its performance for June site demonstration, the multi-UGV system was used to map the outdoor and indoor test areas of the June site demonstration and search for, track, neutralize and localize static and mobile OOIs using PHILS. The number of UGVs used was eight as proposed, and five mobile OOIs and two static OOIs were placed for search, tracking, neutralization and localization.

Figure 27 shows the resulting map and the locations of the neutralized mobile and static OOIs as well as the locations of the UGVs. As the result indicates, nearly the entire map of both the indoor and outdoor test areas was created. In addition, all the mobile OOIs and static OOIs were also identified, neutralized and localized. The result has shown the capability of the developed multi-UGV system to the complete the mission of June site demonstration successfully.

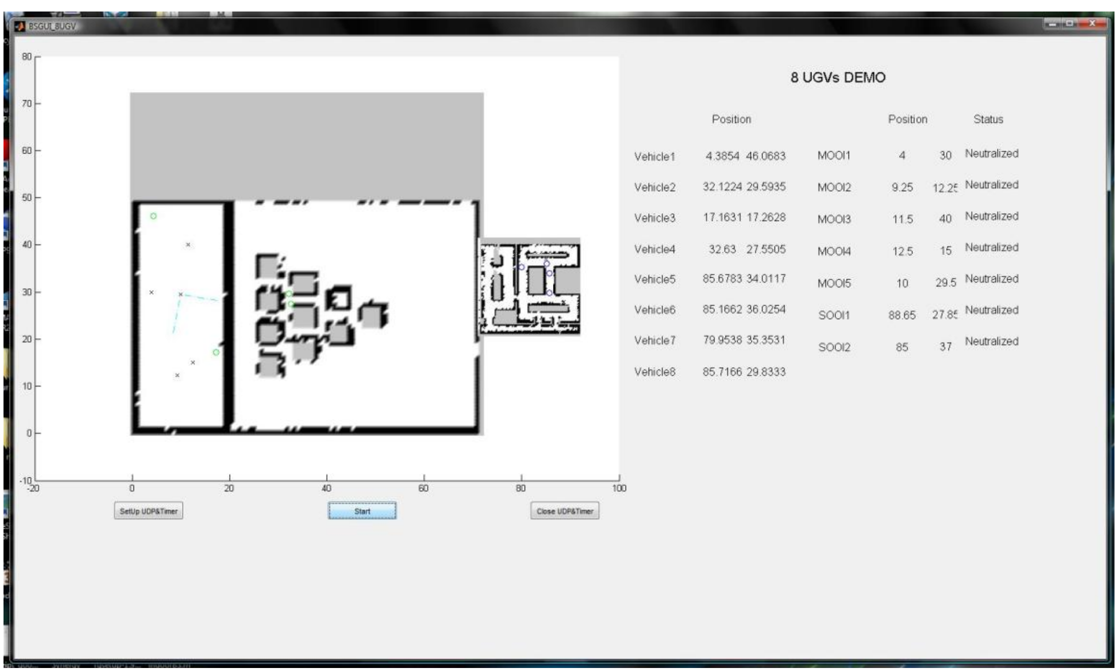

Figure 27 Results of mapping and localization in June site demonstration test area

Having observed the ability of the developed multi-UGV system in June site demonstration test area, Figure 28 shows results of mapping and neutralization in a MAGIC Final like demonstration area. This is aimed at investigating not only the capability of the developed multi-UGV system in various test areas and conditions but also its capability to win in the competition. As evidently seen, an accurate map covering the entire Phases I-III areas has been created. In addition, all the eight mobile OOIs and seven static OOIs have been neutralized. The results demonstrate the capability of the multi-UGV system.

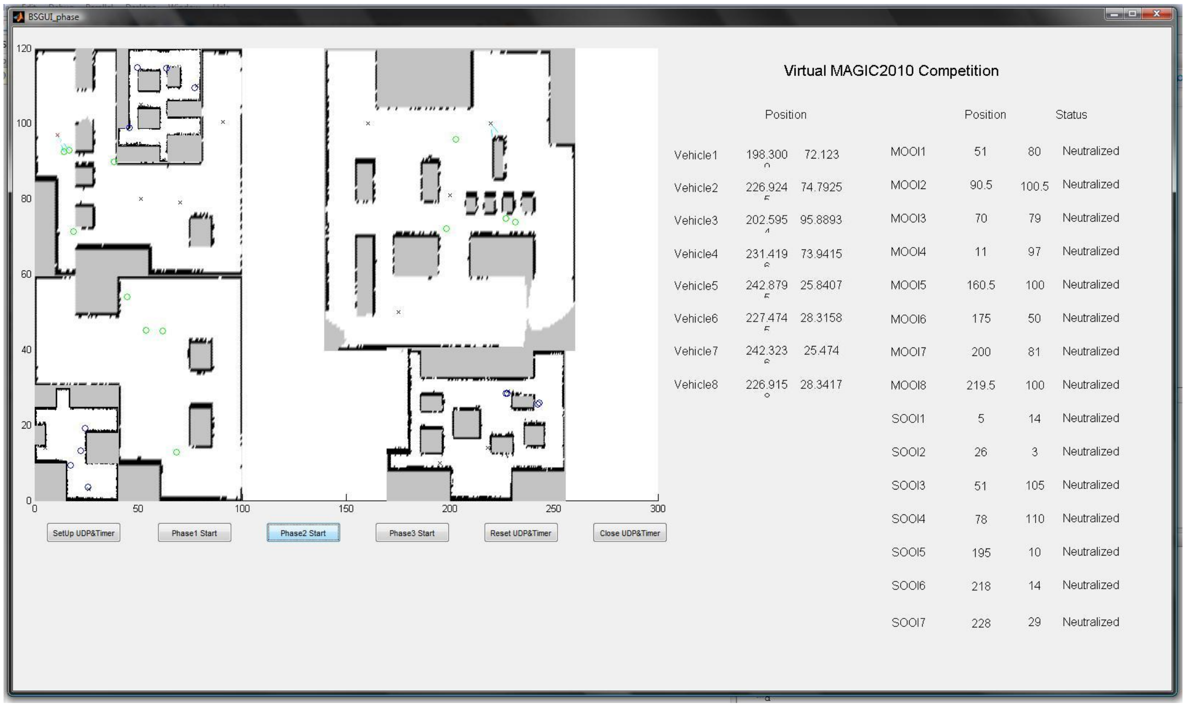

Figure 28 Results of mapping and neutralization in MAGIC Final like demonstration area

In order to finally demonstrate that the virtual test results are comparable to the real test results, the performance of the multi-UGV system was investigated for the mapping of indoor rooms in both virtual and real environments. Figure 29 shows the resulting map. Since details of some corners were not modeled in a virtual environment, small difference in maps can be seen. However, significant similarities in addition the success of mapping of the entire test area can be seen in both the results. This indicates that the reliability of PHIS in quantifying the performance of the multi-UGV system in a real environment.

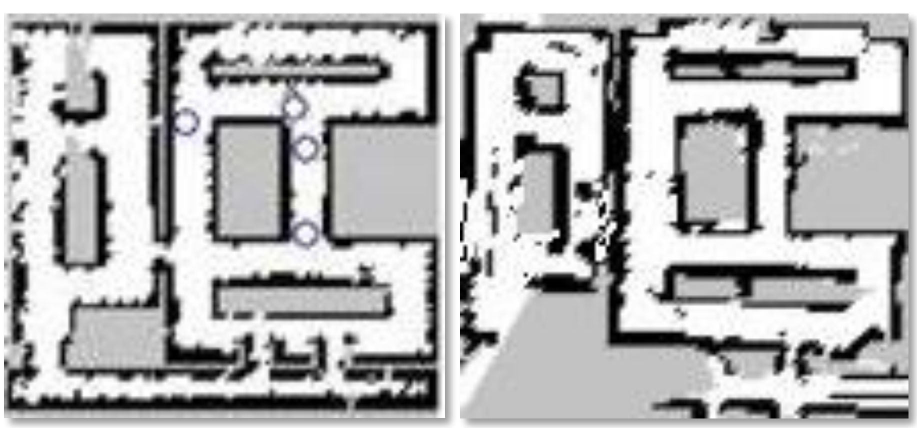

Figure 29 Maps created in virtual environment (left) and real environment (right)

To demonstrate the extensive applicability of the multi-UGV system in the cooperation of real UGVs and virtual UGVs in the same environment, Figure 30 shows the demonstration of three real UGVs and five virtual UGVs in the June site demonstration test area. Similarly to the results by eight simulated UGVs, the three real and five virtual UGVs could build the entire map appropriately. The system has been upgraded to be able to observe real UGVs by virtual UGVs by placing real UGVs at the locations measured by GPS and compass. However, real UGVs are still not able to observe virtual UGVs.

Figure 30 Cooperation by three real UGVs and five virtual UGVs